

**NOAA ENVIRONMENT, SCIENCE AND DEVELOPMENT (ESD) PROGRAM  
FINAL PROJECT REPORT**

**PROJECT TITLE:**

**Communicating Climate Forecasts in South Asia: User Metrics and Climate Risk Management Schools**

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**I PRELIMINARY MATERIALS:**

**A: Project abstract (As per original proposal):**

The utility of forecasting climate variability in the monsoon regions on time scales of 20-25 days is discussed. It is argued that these time scales are probably of greater utility for agricultural and water management in the monsoon regions than forecasts of the seasonally average precipitation abundance or deficit as they have the potential of capturing and defining the large scale active (wet) and break (dry) periods of the monsoons. The extent and scale of these intraseasonal events may be seen in Figure 1. Even though the seasonally averaged rainfall may be normal in a particular region, the occurrence of a monsoon break at the time of planting may cause significant loss reduction of yield. Similarly, an active period occurring near harvest time may also reduce yield through flooding or rainfall damage.

To date, there has been little skill in forecasting these important climate variations. However, a new Bayesian dynamically based statistical model (Webster and Hoyos 2003) has shown considerable skill in forecasting area-averaged precipitation on intermediate time scales. While these forecast would seem to be useful, it is argued that their utility is limited unless the content of the forecast can be communicated to the user community in

a manner that relates directly to their immediate problems. To do this we propose a pilot study that has two principal aims:

- Develops a forecasting measure that combines the probabilistic forecast produced by the physical scientist with the knowledge of the user community of the consequences of the occurrence of a particular meteorological phenomenon. This combination product, which in essence is an outcome based on aggregate risk, is referred to as the User Metric.
- We also propose the establishment, on a trial basis, of Climate Risk Management Schools where the utility of climate variability is introduced. In Bangladesh, the region where we will implement our study, there already exists at the village level Farmer Field Schools run by the Department of Agricultural Extension (DAE) with which we have strong relationships through another program, Climate Forecast Applications in Bangladesh (CFAB). Through the Farmer Field Schools such concepts as integrated pest management are introduced. We plan to take advantage of the existence of this training infrastructure to introduce concepts of climate risk management.

It should be emphasized that these schools will be the location where the forecaster gains information as well. This will be the venue where the user community will provide the information regarding the impact of a particular meteorological event will be have on crop yield, water resources and etc. That is, this is where the two components of the User Metric come together.

#### **B: Objective of the research:**

The aim of the project has been to devise methods of communicating sophisticated technical material to user communities that may not have technical training. The forecasts came in three overlapping tiers:

- 1-6 months utilizing coupled ocean-atmosphere models with hydrological components
- 20-30 day forecasts using a Bayesian “banded wavelet” scheme (Webster and Hoyos (2004))
- 1-10 day forecasts that provide probabilistic forecasts using the ECMWF ensemble output with hydrological models.

This has been accomplished by the creation of the user metric, described above. This has been a one-year pilot and not all of the objectives have been met. The user metrics have been created and tested in Bangladesh but not at the user level. Instead, members of the Government of Bangladesh Department of Agricultural Extensions have viewed the concept. Unfortunately, our USAID funding ran out in early 2004. We utilized Georgia Tech funds to provide forecasts for the summer of 2004 but funding was not continued. It is fortunate that we did, as we were able to foresee the large floods of July 2004 in the seasonal forecasts and make detailed forecasts using the 20-30 day forecasts and the 1-10 day forecasts. Examples of these forecasts can be seen in the publication Webster et al. (2006) attached.

#### **C: Approach:**

We have not had the opportunity to test the method of user metrics in the field. As mentioned in the initial proposal and also by the reviewers, the best we could hope for was to create the metrics, and test them in a limited manner in Bangladesh. Beyond this one-year period, we await continued funding from donors to continue the implementation of the scheme.

The approach is as follows:

- Utilize forecasts from the three-tiered scheme, described above. For illustrative purposes we use the short-term forecasts.
- Obtain information from the user community such as what will be the impact on yield if there were to be river levels of a certain magnitude or if flood levels were exceeded and etc. we note that the implications are very seasonally dependent. For example, the consequences of a flood are far more severe if they occur at harvest time than after planting time. Ditto with droughts.
- Combine the user information with the probabilistic forecasts in the form of a simple visual we call the user metric. This provides the cost/loss information for a host of strategies. It provides the possible loss for ignoring the forecast to information of what the best strategy would be to minimize loss. In other words, the simple graphic provides optimal strategies. Most importantly, it involves information from the user community.

**D: Key beneficiaries:**

The aim of the development of the scheme has been to help farmers make optimal decisions. The conclusions that we reached was that the bridge to this ultimate user community had to be through the GoB Dept. of Agricultural Extension via their District Agricultural Officers.

If further funding for this project becomes available, we will instruct these officers in the use of the metric so that it can be used in the farmer schools. It should be noted that the scheme could be used for all types of applications such as the optimal timing of fertilizer, insecticides and etc.

In anticipation of further funding becoming available, the GoB has designated 6 agricultural test areas throughout the country. We will initially concentrate on these regions.

**E: Budget:**

The total cost of the project was well in excess of the NOAA funding. This was because we needed to continue to produce forecasts during the summer of 2004 to supply data for the user metrics. We used Georgia Tech funds for staff and student support to about the level of \$100K for the year. In that sense, the NOAA OGP funding provided roughly 50% of the costs for the project.

**F: Matching Funds:**

Described in E, above.

## II ACCOMPLISHMENTS

### A: Project timeline and tasks accomplished:

During the year of funding a number of accomplishments were made, some procedural and others in terms of improvements of forecasts and decision tools. These accomplishments were made at workshops, through conversations with scientists and technicians both in Bangladesh and through publications. During the second workshop the forecasts for the previous summer were evaluated and there were discussions about what should occur in the following year.

### B: Summary of findings:

Perhaps the most important accomplishment was persuading the Bangladesh Meteorological Office and the Flood Forecasting and warning Centre that there was little use in a seasonal forecast of discharge. This is because one number (or even a pdf) of river discharge is of little use as it provides little information of when the discharge will be high (flood) and when it would be low (drought). For example, if the discharge of the Ganges were perfectly forecast to be  $X \text{ m}^3/4\text{-months}$ , it would be a useless forecast as  $X$  can be made up of an infinite number of contributions on a smaller time scale. I.e., no information of when a flood would occur is inherent in the seasonal forecast. So the accomplishment was persuading that the system should be adapted to ingest a 3-tier system (1-10 days, 20-30 days and monthly forecasts for a season) which would allow strategic and tactical overlapping decisions to be made.

The next most important accomplishment was demonstrating to the Bangladeshi groups that these three tiers of forecasts were possible and that they could be implemented within the Bangladesh framework. Note that at the start of the project, the Bangladesh Flood Forecast and Warning Centre were able to produce only 2-day forecasts. At the completion of the project, they had added our modules to their scheme and had produced 12-day forecasts that have had surprising accuracy. On an experimental basis, we provided 20, 25 and 30-day forecasts of 5-day average discharge of the Ganges and the Brahmaputra into Bangladesh. The results were extremely encouraging and it is planned (with further funding) to implement the scheme operationally.

I have attached a summary of the paper that describes the results of the exercise. To avoid repetition, I have summarized the main findings with the principal diagrams. These also refer to many of the somewhat repetitious questions referenced in Section III. In summary, the paper expresses all that we have been able to do under the 1-year contract.

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**Rainfall and river discharge forecasting strategies for the developing world in relatively dataless regions.**

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## **Abstract**

During the last decade our understanding of processes that determine the variability of the atmosphere and the climate system have improved to the extent that predictability of some phenomena has become established. The predictability, at least in the short and long term time scales has been translated into. However, the value of forecasts to the extent of how they are used has not improved at the same rate. Arguably, the problem lies with the psychological and physical separation of the scientist or technician who make the forecasts and decision makers and user communities that utilize the forecasts. Furthermore, the separation is exaggerated by the fact that for any one forecast there are many potential applications for different user communities each with different needs and values rendering it extremely difficult for a forecaster to communicate with all users. In essence, sets of decision tools may need to be built for each user class for the same probabilistic forecast. Clearly, this cannot be accomplished by a forecasting center but needs the input of intermediaries (organizational or personnel) and the user communities themselves.

Here we describe one attempt to provide probabilistic forecasts over an overlapping set of time scales and a decision model bridge to allow user communities to make interrelated longer-term strategic and shorter term tactical decisions and thus iteratively hedge against uncertainty. Central to this scheme is the marriage of quantitative user community information with probabilistic forecasts to produce the decision tool in the form of a “user metric”. To illustrate the philosophy of the scheme, we use as examples applications of rainfall forecasts over India and predictions of river discharge for the Brahmaputra and the Ganges both of which have utilized experimentally in a quasi-operational setting since the summer of 2004. The scheme consists of three overlapping sets of forecasts: seasonal (1-6 months) which commences in April and is issued each month, intraseasonal (20-30 days) issued every 5 days and short-term forecasts (1-10 days) issued daily. The short-term and seasonal forecasts use ensemble information from the European Centre for Medium Range Weather Forecast’s (ECMWF) operational and experimental models, statistical dressing of the output and, where necessary, a suite of hydrological models. For the intermediate time scale predictions (20-30 days) we use Bayesian physically based empirical model.

### **1. Introduction:**

(a) **Environmental forecasting in South Asian monsoon climates:**

(b) **The concept of a “useful” forecast:**

(c) **An example: the drought of 2002:**

(d) **Summary of requirements:**

### **2. Examples of tiered overlapping forecasts.**

### **3. Techniques for tiered forecasting**

(a) **Seasonal trends (1-6 months)**

(i) **Models**

- (ii) Bangladesh discharge forecasts
- (b) Intraseasonal forecasts (20-30 days)
  - (i) Model
  - (ii) Discharge and precipitation forecasts
- (c) Short term (1-10 days)
  - (i) Model
  - (ii) Hydrology models

#### 4. Examples of the three-tiered forecasts

#### 5. Communication of forecasts

- (i) Incorporation of a probabilistic forecast of some pertinent parameter (e.g., river discharge, rainfall variability)
- (ii) Incorporation of local knowledge of the impact of an environmental of a given severity.
- (iii) An easily comprehensible and visually decipherable representation of risk: *The User metric*

#### 5. Concluding remarks

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We can summarize the list of general requirements for functional environmental predictions for a user community. These are the basic philosophical building blocks for scientist-user interfaces.

- (i) The forecasts must match the time scales of the major phenomenological time periods in the particular region if they are pertinent to the user community in question. For example in the monsoon regions forecasts should include predictions of seasonal anomalies, intraseasonal variability, and weather.
- (ii) A suite of forecasts should be constructed that are temporally overlapping in order to allow strategic decisions to be made at the longest time period and tactical decisions to be made at the shorter time scales.
- (iii) The forecasts must be probabilistic. Only in this manner can a user of the forecast make a reasoned cost-loss analysis.
- (iv) The forecast should be user specific or can be rendered into information that is useful to the user, and:
- (v) User information should be included into the forecast process.
- (vi) The expectations of a user community should understand the rule that the longer lead-time of a forecast, the less regionally specific a forecast will be. Statistical downscaling techniques or historical data may help but it should be realized that there are basic uncertainty issues that limit the form of a forecast.

It is clear that the problem of creation of useful forecasts comes from an interaction between a user community and the provider of the forecast. It is clear also that quite often the desires of the user and the abilities of the forecaster may not match. However,

through the interaction of the forecaster and the user, the question of what is possible needs to be addressed.

### **C: List of papers, reports, publications and presentations:**

This is a list of presentations made on the subject of forecasting in Bangladesh. Clearly, not all funding has come from the NOAA grant in question. But results from at least partial NOAA support were presented.

2005	New Delhi, India	Modeling monsoon intraseasonal variability with Bayesian and slow manifold modeling. National centre for medium Range Weather Forecasting: Feb 1
2005	San Diego, CA	Intraseasonal variability. American Meteorological Society
2004	Hangzhou, PRC	Experimental three-tier overlapping prediction. WMO Forecasters Conference. November 2004
2004	Hangzhou, PRC	Overview of the physics of the monsoon. WMO Forecasters Conference. November 2004
2004	Baltimore, Maryland	Monsoons (with J. Slingo and R. Mechoso). CLIVAR International Science Conference. June 20
2004	Miami, FL	Monsoons, AMS conference
2004	Charlottesville, VA	Monsoons in a Warming World: Moore Lecture, Department of Environmental Sciences, University of Virginia . April 7,.
2004	Pune, India	Intraseasonal variability of the monsoon: processes and prediction (keynote address: February
2003	Melbourne, Australia	Empirical forecasting of monsoon intraseasonal variability and the utility to numerical prediction. Convection Conference BMRC October, 2003

In addition, less formal presentations were made in Bangladesh during the five visits we undertook in the 0period 2003-2004, which encompassed the period of NOAA funding.

The following publication is outlined above:

Webster, P. J., T. Hopson, C. Hoyos, A. Subbiah, H-. R. Chang, R. Grossman' 2006: A three-tier overlapping prediction scheme: Tools for strategic and tactical decisions in the developing world. In *Predictability of Weather and Climate*, Ed. T. N. Palmer, Cambridge University Press. In press. July 2006.

Webster, P. J., H-. R. Chang, T. Hopson, C. Hoyos, A. Subbiah, 2005: Bridging the gap between research and utility: Development of an overlapping three-tier prediction scheme to facilitate "useful" forecasts. Report of the International Committee of the Third International Workshop: The Global Monsoon System: Research and Forecast. WMO/TD 1266, TMRP Report No. 70Proceedings of the Special WMO Conference on Monsoon Predictability, Hangzhou, PRC, 2-6 November, 2004 p-3-14.

**D: Discussion of deviations from the proposed work-plan:**

As describes many times above, we have established a pathway to the application of the three-tier forecasting system for precipitation and river discharge for Bangladesh. I might add that this is a considerable achievement! We had not the time to instigate the training program but we have the potential of instigating it when further funding arrives.

**III. RELEVANCE TO EFFORTS TO CATALYZE AND ACCELERATE THE USE OF SCIENCE AND TECHNOLOGY IN THE RESOLUTION OF KEY RESOURCE MANAGEMENT CHALLENGES**

**A: Contribution of project to ability of institutions to adapt to climate variability and change (footprint):**

I believe that we have left a considerable footprint in Bangladesh. Not only have we developed a 3-tier system, we have shown that there are benefits to its complete implementation. Furthermore, through a partnership with ECMWF, we have established a pathway for Bangladesh scientists to work directly with the European Union. This was accomplished by a drawing up of an MOU between ECMWF, the Bangladesh Meteorological Service and Georgia Tech.

**B: Impact on actual decision making related to climate. Environment and resource management**

We have developed a three-tier system that provides an array of overlapping forecasts. We believe that they are only useful if all three are provided. Perhaps the least useful (and this goes for all of the monsoon region) are the seasonal forecasts. We have given detailed probabilistic forecasts that show considerable skill (see attached paper) allowing an extension to 12 days of the 2-day forecast that BMD/FFWC could do before our arrival. Incorporation of the 20-30 day forecasts into their system is next noting that the largest variability occurs on these time scales. The Bangladeshis have found our forecasts most useful.

**C: Impact of project results on furthering the integration of research and applications at international, national and local levels**

See IIIA above and the continuing relationship between the Bangladeshi institutes and ECMWF and Georgia Tech.

**D: Relationship of project work to other work funded by NOAA.**

None

**E: Specific contributions:**

I am sorry, I do not understand this question.

**IV. LINKAGES**



**A: Description of interactions with decision makers together with list of collaborators.**

The interactions have been many and they are very varied. We interact with two main organizations: the Flood Warning and Forecast Center (FFWC) and the Bangladesh Meteorological Department and specifically with their directors Dr. Akhtar Hussein and Mr. Hossein. To date we have supplied forecasts generated at Georgia Tech and utilized and evaluated by these two organizations in Bangladesh. We also deal directly with NGOs most notably CEGIS in Bangladesh and the Asian Disaster Prevention Center in Bangkok, Thailand.

**B: Description of interactions with broader research and applications programs**

Such interaction has occurred through the presentation of papers on forecasting in the monsoon regions at national and international conferences.

**C: Identify key research needs not currently undertaken**

These have been described previously. Simply, not enough time to do everything in one year.

**V. GRAPHICS: PLEASE INCLUDE THE FOLLOWING GRAPHICS AS ATTACHMENTS TO YOUR REPORT**

The pertinent graphics are included in the attached paper.

**VI. WEBSITE ADDRESS FOR FURTHER INFORMATION (IF APPLICABLE)**

<http://webster.eas.gatech.edu> and follow pointers to CFAB

# **Rainfall and river discharge forecasting strategies for the developing world in relatively dataless regions.**

*This is a draft version of the paper that will appear in In Predictability of Weather and Climate, Ed. T. N. Palmer, Cambridge University Press.*

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## Abstract

During the last decade, our understanding of processes that determine the variability of the atmosphere and the climate system have improved to the extent that predictability of some phenomena has become established. The predictability, at least in the short and long term time scales has been translated into. However, the value of forecasts to the extent of how they are used has not improved at the same rate. Arguably, the problem lies with the psychological and physical separation of the scientist or technician who make the forecasts and decision makers and user communities that utilize the forecasts. Furthermore, the separation is exaggerated by the fact that for any one forecast there are many potential applications for different user communities each with different needs and values rendering it extremely difficult for a forecaster to communicate with all users. In essence, sets of decision tools may need to be built for each user class for the same probabilistic forecast. Clearly, this cannot be accomplished by a forecasting center but needs the input of intermediaries (organizational or personnel) and the user communities themselves.

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Here we describe one attempt to provide probabilistic forecasts over an overlapping set of time scales and a decision model bridge to allow user communities to make interrelated longer-term strategic and shorter term tactical decisions and thus iteratively hedge against uncertainty. Central to this scheme is the marriage of quantitative user community information with probabilistic forecasts to produce the decision tool in the form of a "user metric". To illustrate the philosophy of the scheme, we use as examples applications of rainfall forecasts over India and predictions of river discharge for the Brahmaputra and the Ganges both of which have utilized experimentally in a quasi-operational setting since the summer of 2004. The scheme consists of three overlapping sets of forecasts: seasonal (1-6 months) which commences in April and is issued each month, intraseasonal (20-30 days) issued every 5 days and short-term forecasts (1-10 days) issued daily. The short-term and seasonal forecasts use ensemble information from the European Centre for Medium Range Weather Forecast's (ECMWF) operational and experimental models, statistical dressing of the output and, where necessary, a suite of hydrological models. For the intermediate time scale predictions (20-30 days) we use Bayesian physically based empirical model.

## **(1) Introduction:**

### **(a) Environmental forecasting in South Asian monsoon climates:**

Of all of the peoples of the planet, those who inhabit the monsoon regions are most vulnerable to weather and climate variability and most in need of accurate and timely environmental forecast. Figure 1 shows the geography of South Asia and the locations referred to in the text. In India, for example farming areas that depend upon rainfall (non-irrigated land) map directly on to the most impoverished regions in the country. Inhabitants of the non-irrigated regions are most susceptible to weather and climate anomalies where unexpected periods of drought or heavy rainfall can be especially costly. Irrigated sectors of the country are less susceptible to short term weather variability, at least in terms of short-term droughts. But there is an equal susceptibility to periods of heavy rainfall especially near harvesting times, or to prolonged drought such as occurred in the summer of 2002. In general though, in all regions of South Asia the strong argument can be made that forecasts of weather and climate would reduce the impact of extreme meteorological and hydrological events. In all areas useful and timely forecasts, rendered into a form useful to the user communities, will lead towards an improvement of agricultural practices. In irrigated lands skillful and timely forecasts can lead to useful water resource management and the partition of use between irrigation and power generation.

Figure 2a illustrates the multiple time scales of the Indian monsoon, The figure shows precipitation over central India (see Figure 1) during the summer for the four years plotted as 5-day averages from the spring through the fall. The background curve is the long-term climatological precipitation. Each year is different indicating distinct interannual variability. Within each season there are marked periods of prolonged precipitation ("active" periods) and rainfall minima ("break" periods). These occur randomly throughout the monsoon summer season as indicated by the absence by the smoothness of the long-term climatological precipitation. Within each of the active periods there is considerable rainfall variability (Figure 2b) denoting monsoon weather.

During the last decade there have been marked advances in our understanding of the variability of monsoon rainfall over a wide range of time scales (e.g., Webster et al. 1998) perhaps because of the attention the tropics has received in the World Climate Research Programme's (WCRP) Tropical Ocean Global Atmosphere project (TOGA) and the more recent the Climate Variability and Predictability project (CLIVAR). A major scientific objective of CLIVAR is to understand the interannual and intraseasonal dynamics of the atmosphere-ocean-land system of the monsoon with the aim of translating this scientific understanding into a predictive capability.

Despite the scientific advances, predictability has remained elusive on time scales longer than a few days related to the forecasting of monsoon weather embedded in the large scale monsoon circulation. Forecasting or even simulating intraseasonal 20-40 day variability by numerical techniques has proven extremely difficult despite the fact that next to the annual cycle variance in this spectral band dominates the monsoon.

Numerical attempts to foreshadow seasonal variations of the monsoon have not been particularly successful at this stage either. Empirical schemes, which have been the main method of forecasting interannual monsoon variability, attempt to relate large scale forcing from the El Nino-Southern Oscillation (ENSO) phenomenon to the future state of the monsoon. However, since the mid-1980's, skill using empirical methods has diminished significantly. For example, when the largest El Nino of the twentieth century occurred in 1997-1998, the Indian monsoon was essentially normal. During a relatively weak El Nino (2002-2003) India suffered the worst drought in decades. Both of these recent years defied the canonical El Nino-Indian monsoon drought relationship suggested by Rasmusson and Carpenter (1982). Similar anomalous responses (or lack of response) were found in Australia which was spared the canonical drought in 1997/1998 but faced the worst

drought in a hundred years in 2002. It may be argued that the impact of these two El Ninos depended on subtle differences in the westward extent of the anomalous warm pool. For example, recent research results:

*"Different El Ninos can have significantly different impacts on Australian rainfall, for example, the 1997/8 El Nino had little impact on Australia whereas the relatively weaker 2002/3 El Nino had a significant impact. The differences in ocean and large scale atmospheric structure over the tropics and Australia during the 2002/3 and 1997/8 El Nino have been compared using the NCEP re-analysis. There were large scale differences in the topical circulation that may explain the different impacts of the two El Nino's, which may be related to the location of the SST maxima in the tropical Pacific."* (Personal communication: Drs. Guomin Wang and Harry Hendon, Bureau of meteorology Research Centre, Melbourne, Australia)

It is true that our ability to forecast ENSO variability is one of the great triumphs of climate dynamics but forecasting future subtle spatial differences in the location and magnitude of the Pacific SST anomaly may have to wait considerable technological advances. Even if such forecasts could be produced, there is the question of the lack of predictability across the boreal spring (e.g., Webster and Yang 1992) and the minimal lead time that would be available to implement the forecast in India, Indonesia and Australia lies somewhere in the future. These are the realities that must be faced in dealing with interannual prediction in the monsoon regions.

#### **(b) The concept of a "useful" forecast:**

Even if a forecast of El Nino and its influence on the South Asian monsoon were available, would that in itself constitute a useful prediction? Here we define "useful prediction" in its broadest sense. A useful forecast, for example, requires a bridging of the gap between a "broad-brush" seasonal forecast over a large area (e.g., a forecast of the seasonal anomaly in the All India Rainfall; and index representing rainfall over the entirety of India) to a forecast that can help a decision maker in a particular location (e.g., a farmer, water resource manager, district agricultural extension officer, governmental official, politician and etc.) take action to hedge against uncertainty in the future state of weather and climate. For example, consider the role of the agricultural extension officer whose purpose is to transfer highly technical information to members of an agricultural community who may not be privy to environmental considerations or technical advances that would help in agricultural practices. The officer's role is to provide advice on issues such as type of crop or species to be used in a given state of the environment, what type of pesticide or fertilizer should be applied and to advise on the quantity and the timing of their. But from where, and in what form, does the agricultural officer receive information to make these suggestions to the farming community? And how does the officer receive training in order to convey this information in a confident and credible manner? In the Climate Forecast Application in Bangladesh (CFAB) project, we have attempted to bridge the gap between probabilistic forecasts and their application in real circumstances.

Zhu et al. (2002) postulated a necessary condition for the provision of a useful forecast. They note that each day individuals, communities, administrations and etc., have to make decisions to hedge against uncertainty. For example, should one plant a crop today or wait until tomorrow or the following week to take advantage of a proposed rainy period or avoid a rainless period following planting? Should one spray pesticide on one particular day or another and etc. in order to optimize the impact of the chemical and minimize the loss through excessive rainfall? Consider a farmer who is faced with the problem of obtaining the maximum yield from his crop. The farmer is faced with many choices: he could wait and harvest a crop at full maturation (say in ten days) and possibly achieve full yield but taking the chance that adverse weather or floods may seriously reduce the yield. He could harvest partially through the forecast period perhaps taking advantage of present weather and the potential that part of his crop might reach maturation, or he could harvest totally and immediately knowing that there would be a reduction in total yield but that there would be no

further risk of falling below that level. Without environmental information, the strategy that the farmer may choose any of the options can be chosen at random. Without probabilistic information about the future state of the environment, it is not possible to undertake a cost-benefit or risk analysis and hedge against uncertainty. Following Zhu et al. (2002), only probabilistic information is useful.

The problem of providing “useful forecasts” goes beyond producing a probabilistic forecast of the rainfall for the coming season. No matter how skillful the forecast may be, there is no guarantee that the forecast will be useful to a regional user groups. The problem goes beyond the downscaling of forecasts of large scale forecasts to some region which is itself a major problem. Figure 3a from Webster and Hoyos (2004) underlines the problem of inferring regional anomalies from macro-scale forecasts. Even when the overall rainfall is decidedly above or below average, there are many regions which are of the opposite sign average. Only in the cases of extreme anomalies (e.g., 2002) would most districts in India tend to be below average. The same problem exists in the temporal variation of rainfall. Figure 3b shows the variability of rainfall over central India binned as functions of the overall monsoon rainfall. The active and break periods possess minimal temporal clustering relative to the overall seasonal rainfall. That is, irrespective of the total rainfall for the season, there is no knowing when the first active or break period or any subsequent variability of the monsoon will occur. This means that even in a “good” monsoon year, it is possible that the first break will be so timed as to adversely impact the crop yield. Thus a useful forecast is one that provides relevant climate variables at the local level on a time scale that allows changes in plans if necessary.

The definition of what the relevant climate variables are is by the user community. For example, the agricultural extension officer is aware of the environmental conditions that will allow some pest to thrive. The officer is also aware of the effectiveness of a particular pesticide and the environmental conditions that will allow it to eradicate the pest. The officer may want to know if there is a window of four rainless days that can be used for application in order to compare the cost of applying the pesticide versus the profit from a successful application relative to the predicted weather. Of course, providing all of the information that a user may want may not possible for all users in all environmental circumstances. But the message here is that the user is an essential partner in the development of useful forecasts and that the user can provide quantitative information

It is obvious from Figures 2 and 3 that monsoon variability occurs on multiple time scales. Within the summer rainy season there are successive active (wet) and break (dry) monsoon periods on time scales of 20-40 days acting in a sense of an evolving envelope within which weather is modulated. Within an active period extreme rainfall events may be embedded increasing the potential for flooding. On the other hand, breaks in the monsoon, occurring at times that are agriculturally sensitive (particularly planting and harvesting) may be devastating such as in 2002 over most of India. Thus, the information needed for a decision maker (e.g., our agricultural extension officer) also has different time scales. Therefore, another necessary condition for a useful forecast is that covers the major variance intervals in a particular climate system. For the monsoons, this means seasonal variability, intraseasonal variability and monsoon weather.

For example, consider the problem of a decision maker who has been told that there is a high probability to expect a slightly below average seasonal monsoon rainfall on the scale of the subcontinent. The agricultural expert may decide to choose a drought resistant seed but he is still faced with the immediate problem of when to plant. To optimize planting it is necessary to know the probability of not only when the first rains will occur but the probable duration of these early season rains. That is, besides an indication of the overall seasonal rainfall, the timing of the onset must be known *and* the timing of the first break in the monsoon and how long it will persist.

### **(c) An example: the drought of 2002:**

The summer of 2002 provides a useful example (Figure 2a) where the overall seasonal precipitation for the season turned out to be 20% below average although official forecasts predicted

slightly below average seasonal rainfall. Note that the official Indian Meteorological Department forecast was deterministic: that is there was no probability attached to the forecast. But the problem encountered by India during 2002 came not from the failure of the overall forecast (or its determinism) following the monsoon onset. With a seemingly successful onset of rain in June (albeit slightly later than average) planting commenced. However, the prolonged break period in July was not predicted. Subbiah (2004) comments on the mid-summer drought and what might have occurred if forecasts on intraseasonal time scales had been available.

*"... The dry spell starting from mid-July to the first week of August 2002 in most parts of India, caused serious dislocations in water management and agricultural operations. The revival of monsoon conditions in the second week of August (see Figure 2) eased the water stress situation to some extent. Assuming that a prediction of the July drought had been available by the third week of June 2002, and of the revival of the monsoon rains by second week of July 2002, the forecasts would have made the following differences. In most parts of India agriculture operations start in second week of June and farmers make heavy investments during this period for land preparation, seedbed preparation, nursery raising and transplanting of seedlings. The water resource managers make decisions on allocation of water for various purposes (irrigation, hydroelectricity generation) on the assumption of normal rains. The prediction of likely dry spell in mid-June with a lead-time of weeks could have motivated farmers to postpone agriculture operations, saving investments worth of billions of dollars. The water resource managers could have introduced water budgeting measures, such as minimizing water availability for water consuming crops and maximizing water for low water consuming crops, and by rationing water use for hydroelectric power. Similarly, the prediction of the revival of monsoon rains by the second week of July would have motivated the planners and farmers to undertake contingency crop-planning by mobilizing resources such as seed availability and credit for choosing suitable crop varieties, carrying out mid-season corrections and undertaking crop life saving measures. These actions would have helped to preserve farm income and ensured food security and reduce relief expenditure by at least 60% of the present cost (i.e., around 6 billion US\$). Water resources could have been used to raise fodder crop in northwest India thus reducing the need for transportation of fodder from distant places at a huge cost. In summary, a 20-day forecast during monsoon 2002 in India could have mitigated the impacts of the droughts in several parts of India to a significant extent....".*

Subbiah's comments on the 2002 drought in India describes well the forecast requirements of the agricultural and water resource managers in South Asia. There are no simple solutions and it is necessary to think beyond normal techniques and procedures to useful information.

#### **(d) Summary of requirements**

We can summarize the list the general requirements for functional environmental predictions for a user community.

- (i) The forecasts must match the time scales of the major phenomenological time periods in the particular region if they are pertinent to the user community in question. For example in the monsoon regions forecasts should include predictions of seasonal anomalies, intraseasonal variability, and weather.
- (ii) A suite of forecasts should be constructed that are temporally overlapping in order to allow strategic decisions to be made at the longest time period and tactical decisions to be made at the shorter time scales.
- (iii) The forecasts must be probabilistic. Only in this manner can a user of the forecast make a reasoned cost-loss analysis.
- (iv) The forecast should be user specific or can be rendered into information that is useful to the user, and:

- (v) User information should be included into the forecast process.
- (vi) The expectations of a user community should understand the rule that the longer lead-time of a forecast, the less regionally specific a forecast will be. Statistical downscaling techniques or historical data may help but it should be realized that there are basic uncertainty issues that limit the form of a forecast.

It is clear that the problem of creation of useful forecasts comes from an interaction between a user community and the provider of the forecast. It is clear also that quite often the desires of the user and the abilities of the forecaster may not match. However, through the interaction of the forecaster and the user, the question of what is possible needs to be addressed.

In the following paragraphs we will outline a forecasting system that provides the user community with a best use of available information. We will use the example of an operational system that we have implemented in Bangladesh for the forecasting of river discharge into the country in addition to regional precipitation forecasts. This system, broadly described as the “three-tier” forecasting system, produces overlapping forecasts on seasonal, 20-30 days and 1-10 days. We will then address the problem of how to interface the products of the physical scientist with the needs of the user community through the development of a “user metric” which allows a simple depiction of hedging strategies.

## **(2) Examples of tiered overlapping forecasts:**

We provide two examples of forecasts utilizing the three-tier system described in earlier. We choose Bangladesh (where summer flooding is a major problem) and rainfall in the Ganges catchment region and in central India. The latter two regions are major agricultural regions in India. Bangladesh is a deltaic country that lies at the confluence of three major rivers: the Ganges, the Brahmaputra and the Meghna and is thus susceptible to flooding from one or a combination of all three rivers. Flooding occurs each year in Bangladesh but in different parts of the country and occurs irregularly throughout summer sufficiently to disrupt planting and harvesting cycles and cause local social disruptions. Occasionally the flooding is severe and prolonged as in the summer of 1998 when 90% of the country was inundated for nearly 3 months. Bangladesh flooding is often out-of-phase with rainfall over peninsular and central India. For example, during the summer of 2002, while most of India was under severe drought conditions, floods occurred over Bangladesh as the Brahmaputra passed its critical discharge levels. This occurred because during break periods of the monsoon, precipitation shifts north over the foothills of the Himalayas in the catchment area of the Brahmaputra. Flooding during active periods of the monsoon comes from the overflow of the Ganges.

We discuss briefly the progress that has been made during the last three years in developing a three-tier forecast system of river discharge, flood warning and precipitation for Bangladesh and a number of regions of India. The forecasting schemes are based especially upon our increased understanding of the monsoon system and, to some extent, on an improving ability of models to simulate the monsoon system. The CFAB project was formed as a joint effort between Georgia Institute of Technology, University of Colorado, the Asian Disaster Preparedness Centre (ADPC) and ECMWF. The basic aims of CFAB lie in four main areas:

- (i) The generation of a river discharge and precipitation operational forecasting system that would be available in real-time with forecasts provided on a three-tier time system: seasonal outlooks (1-6 months), intermediate (20-30 days) and short term (1-10 days) using state-of-the-art models or with models developed specifically for the regional problem. These time scales were chosen as they match statistically significant spectral maxima that are found in monsoon variables. In addition, they were chosen to allow strategic decisions to be made relative to seasonal outlooks and tactical decisions or reorientations at the intermediate and short time scale;



- (ii) Creation of a collaborative enterprise between international (US and Europe) and Bangladeshi (and eventually Indian) partners for the forecasting of the probability of floods on time scales of days to months leading to the transfer of the techniques and technology to our appropriate partners;
- (iii) The development of an infrastructure that allows the application of the forecasts by regional scientists, engineers, agricultural extension workers, disaster relief organizations;
- (iv) The development of methods and decision tools so that the forecasts are directly applicable to the user sectors; and;
- (v) The transfer of the forecasting technology to the Bangladeshis in a form that is immediately useable in an operational sense and modifiable for other uses and eventually to the larger monsoon community of Asia and Africa.

Considerable progress has been achieved in the implementation of (i), (ii) and (iii). During the summer of 2003 and 2004, operational forecasts were made available for the long-term and short-term forecasts during the entire season on an experimental basis. Seasonal outlooks (i.e., river discharge forecasts at 1, 2, 3 ... 6 months were provided each month. Short-term forecasts (1-10 days) were issued each day for both 2003 and 2004. These latter forecasts were used extensively by various water resource groups in Bangladesh. Intermediate 20-30 day forecasts were issued every five days starting in the middle of the 2004 season<sup>1</sup>.

Forecasting river discharge and translating these forecasts to flood forecasts is a special challenge in Bangladesh. If floods in Bangladesh can be forecast with sufficient lead-time and accuracy, actions could be taken across the country that could lessen the impact of the floods. However, until recently, the ability to forecast floods in Bangladesh has not existed for the following reasons:

- (i) Floods can be forecast at a point downstream by knowing the river flow at some point upstream in conjunction with a local precipitation forecast in addition to a hydrological/land use model. Based on this information, simple regression forecasts can give fairly accurate short-term estimates of river discharge. However, Bangladesh does not receive any upstream river flow information from India and the only information that Bangladeshi authorities concerned with flood forecasting are the river flows they measure staging points where the two major rivers enter Bangladesh and at other points within Bangladesh (Figure 1). From these data it has been possible to forecast flood levels in the interior and in the south of Bangladesh but with only 2 days lead time for the central portion of Bangladesh. CFAB decided to extend the lead-time by assuming that the Ganges and the Brahmaputra were ungauged river basins and by using a variety of model types.
- (ii) The physical factors that determine the rainfall over the Ganges/Brahmaputra catchments have only recently been understood. Hitherto, numerically-based deterministic (or probabilistic) forecasts of rainfall on any time scales have not been available to the Bangladeshis. In fact, to date the Bangladeshis do not have any meteorological facility. India has some but this is restricted to relatively short range.

In the following sections of the paper, we show examples of the three tier forecasting system for Bangladesh. In essence, a good hydrological forecast must arise essentially from a good precipitation forecast, especially since we have to treat the Ganges and Brahmaputra as ungauged river basins. So, as byproducts of the flood forecasts are regional precipitation forecasts which we will show as well as river discharge. In the next section, we will outline briefly the techniques

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<sup>1</sup> The CFAB project is described in detail at: <http://cfab.eas.gatech.edu/cfab/cfab.html>, while real-time forecasts can be found at <http://cfab2.eas.gatech.edu>.

employed in each of the three tiers but leave details of the schemes to published papers and the web-sites listed above.

### **(3) Techniques for tiered forecasting:**

There exists within the World Climate Research Programme (WCRP) a large number of components, each dealing with different time scales and each, to some degree, with simulation and prediction. A recently adopted program Predictability Assessment of the Climate System (PACS) has been set up in order to address the common needs of the diverse WCRP programs. PACS calls for a "seamless modeling approach" in which one "unified" model would attempt to forecast variability and climate on all time scales. With this vision, variability on the time scales of weather (1-10 days) would be predicted with the same model as intraseasonal variability (20-40 days) or interannual variability and so on. Such a proposal has many positive aspects. For example, Palmer and Webster (1994) suggested that a unified model approach would lead to better predictions on all time scales on the assumption that the best climate model would be a weather prediction model and, conversely, the best weather prediction model would be the best climate model. The rationale was that a model, used for the dual purpose of weather and climate prediction would undergo significant scrutiny on many time scales. In this manner, systematic errors in seasonal means, for example, which could influence the frequency and timing of weather events could be minimized. At the other end of the scale, systematic high frequency errors could be minimized before they produce errors that erode lower frequency spectral bands.

In the future, quite possibly, through the concept of the unified model one may look forward to significant advances in prediction, on the one hand, and efficient utilization of resources, on the other hand. Unfortunately, there are real problems that need to be addressed and there are distinct model problems that preclude the use of a unified model at this time. In particular, models have great difficulty in predicting, or even simulating intraseasonal variability. Given the importance of the intraseasonal climate mode in the monsoon regions (see Figures 2a,b), this problem is a considerable problem. Clearly, other techniques will have to be used to fill this predictability gap.

Rather than using one model to predict the three pertinent time scales, we take the more pragmatic approach and use three different techniques for each of the tiers. The shortest and longest predictions use ECMWF model output although from different models. The intermediate prediction time scale uses a Bayesian empirical technique using sets of observed data. The overall philosophy of the overlapping approach is shown schematically in Figure 4.

(a) precipitation and river discharge are made each day with lags of 1 to 10 days.

**Seasonal trends (1-6 months):** We have the choice of developing empirical forecasts using output from coupled ocean-atmosphere models. We choose the latter as with the latter estimates of probability accompany the forecasts. The system is summarized below.

(i) Models: In addition to the short-term forecasts discussed throughout this thesis, Climate Forecast Applications in Bangladesh (CFAB) also produces 1 to 6-month in advance forecasts of discharge and rainfall for Bangladesh during the monsoon season (May through October). These forecasts are done both for the combined and individual catchments of the Brahmaputra and Ganges basins and are based on the European Centre for Medium-Range Weather Forecasts 41-member seasonal ensemble precipitation forecast. The ECMWF seasonal model utilizes an ocean model based on HOPE (Hamburg Ocean Primitive Equation model) version 2 (Latif et al. 1994, Wolff et al. 1997). The model is global and has 29 vertical levels. Horizontal discretisation is on an Arakawa E grid with a variable grid spacing: the zonal resolution is  $1.4^\circ$  and the meridional resolution varies from  $0.3^\circ$  in the equatorial region (within 10 degrees of the equator), smoothly increasing to  $1.4^\circ$  polewards of  $30^\circ$ .

The atmospheric component of the coupled ECMWF seasonal model is the ECMWF IFS (Integrated Forecast System) model version 23r4. Except for resolution, this is the same model as

was used for NWP in early 2001. It is also the same cycle as is used in ERA 40, except that there are 40 levels in the vertical, compared to the 60 used in ERA40 and the horizontal resolution used for the atmospheric component is TL95. The spectral representation is used only for the dynamical part of the model calculations. All of the model physical parameterization (including clouds, rain and the land surface) are calculated on a Gaussian grid with about 1.875° spacing. The atmospheric model uses a two time-level semi-Lagrangian scheme for its dynamics with a 1-hour time step.

(ii) Precipitation forecasts: "Relative" Precipitation Forecasts CFAB distributes "relative" forecasts of monthly-average precipitation; specifically, what the probability is that the given month to be forecast will be in the lowest quintile, 2<sup>nd</sup>, 3<sup>rd</sup>, 4<sup>th</sup>, or highest quintile of climatology (other quantile increments are also produced). To produce these relative forecasts, the first step was to develop a "model-space" climatology of catchment-averaged precipitation to compare against (see Hopson 2005) using the ECMWF seasonal model. "Model-space" climatologies were developed for each month of the monsoon season and for each forecast lead-time (i.e. 1-month forecast, 2-month forecast, etc.) individually, and were derived using the 5-member ensemble precipitation hindcasts from 1987 to 2001 and 40-member ensembles from 2002 to the present of the ECMWF seasonal model using the "kernel" approach described in Chapter 2.5. The implicit assumption was made that taking all ensemble members together over this time-span sufficiently defined the climatological "attractor". Using this "model-space" climatology, the current year's forecasts were compared to this "climatology" to determine the forecasts relative ranking (nearest quantile) within this model-space. Once the quantiles of all the forecasts were determined, they were "binned" into the larger categories desired (i.e. 0 to 20. Note that these calculations were done in "model-space" solely because of large biases in the forecasts meant that the forecasts couldn't directly be compared to the "observed" climatology.

To produce "actual-valued" precipitation forecasts of monthly-averaged precipitation (as opposed to the relative forecasts discussed in the previous section), an "observational-climatology" was also determined using rain gauge data from 1979 to 1996, and combined raingage and satellite-derived precipitation data from 1996 to the present using data from the Global Precipitation Climatology Project (1996 to the present) and from the CMORPH project (2002 to the present). Using a "quantile-to-quantile" mapping technique developed by Hopson (2005), the forecast quantiles discussed above were used to extract the equivalent quantiles in "observational-space". In this way significant biases were removed and forecasts were made that corresponded statistically to the "observed climatology".

(iii) Discharge Forecasts: The principal behind CFAB's discharge forecasts is that monthly-averaged precipitation is significantly correlated with monthly-averaged discharge. Therefore, if say above(below)-average monthly precipitation is forecast, this directly implies a forecast of above(below)-average monthly discharge. To explore this relationship between precipitation and discharge, monthly-averaged "observed" precipitation was correlated with lagged monthly-averaged discharges for the Ganges (at the entry point of the Ganges into Bangladesh at Hardinge Bridge), the Brahmaputra (at the border entry point at Bahadurabad), and the combined border Ganges-Brahmaputra were derived for the months of June through September for 17 years (1987-2003). The following correlations were calculated and are shown in the following tables.

Lag	Correlations		
	Pearson	Spearman	Kendall
0 days	0.39	0.37	0.25
23 days	0.76	0.81	0.80
29 days	0.71	0.75	0.54

**Table 1: Correlations of Monthly-averaged precipitation with monthly-averaged discharge at different lags for the Ganges basin. The Pearson correlation coefficient, Spearman rank correlation, and Kendalls rank correlation are given at 0-lag, optimal-lag, and 30-day lag.**

In Table 1, it should be noticed that at the optimal lag for discharge after precipitation for the Ganges catchment is at 23 days, with a Pearson correlation coefficient of 0.76; the optimal lag for the Brahmaputra is 10 days, with a correlation of 0.60; for the combined catchments the optimal lag is 17 days with a correlation of 0.65. These are all statistically significant. Armed with these correlations, forecasts of precipitation can then be used to derive discharge.

Lag	Correlations		
	Pearson	Spearman	Kendall
0 days	0.41	0.37	0.26
23 days	0.60	0.56	0.41
29 days	0.42	0.42	0.31

**Table 2: Correlations of Monthly-averaged precipitation with monthly-averaged discharge at different lags for the Brahmaputra basin. The Pearson correlation coefficient, Spearman rank correlation, and Kendalls rank correlation are given at 0-lag, optimal lag, and 30-day lag.**

Actual discharge magnitudes can be forecast using the "quantile-to-quantile" mapping technique as was used for precipitation. The first step in this process was to develop a monthly-averaged discharge "climatology", which was done for each month individually, but at the respective optimal lags given above for each catchment. Quantiles of discharge were then extracted that were equivalent to the forecasted (1- to 6-month forecasts) precipitation to generate (1- to 6-month + lag) forecasted flow rates. (in cubic meters per second). Correlations are listed in Table 2.

**(b) Intraseasonal variability (20-30 days):**

Given the difficulty numerical models have in simulating and predicting intraseasonal variability in the tropics and subtropics, we use empirical schemes to forecast on the intermediate tier. Specifically, we use the physically based Bayesian scheme of Webster and Hopson (2004).

Predictors			
#	Field	Region	Data Source
1	Arabian Sea 10 m zonal wind	10°N-15°N, 65°E-75°E	NCEP <sup>+</sup>
2	Central India OLR	15°N-25°N, 70°E-85°E	NOAA*
3	Central India Soil Moisture	15°N-25°N, 70°E-85°E	NCEP <sup>+</sup>
4	Equatorial Indian Ocean 200 mb zonal wind	5°S-5°N, 70°E-85°E	NCEP <sup>+</sup>
5	Somalia Jet 925 mb meridional wind	2°S-8°N, 65°E-75°E	NCEP <sup>+</sup>
6	Arabian Sea 10 m meridional wind	10°N-15°N, 65°E-75°E	NCEP <sup>+</sup>

7	Central India surface pressure	15°N-25°N, 70°E-85°E	NCEP <sup>+</sup>
8	Equatorial Indian Ocean 10 m zonal wind	5°S-5°N, 70°E-85°E	NCEP <sup>+</sup>
9	Equatorial Indian Ocean OLR	5°S-5°N, 70°E-85°E	NOAA*
10	Tropical 200 mb easterly jet index	20°N-30°N, 70°E-100°E	NCEP <sup>+</sup>

\*Estimates of outgoing long-wave radiation from the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites (Gruber and Krueger 1984, Liebmann and Smith 1996).

<sup>+</sup>NCEP/NCAR reanalysis data has been obtained from <http://www.cdc.noaa.gov/cdc/reanalysis/>. The data are described by Kalnay et al. (1996)

**Table 3: Predictors used in the MISO statistical prediction scheme. Predictors are chosen so as to constitute a complete description of the evolution of the MISO.**

(i) Model: The model is based on the concept that banding the time series of predictands and predictors will minimize the high frequency errors projecting onto the lower frequency signal. This is accomplished by first selecting a predictand such as precipitation over Ganges catchment or Brahmaputra discharge into Bangladesh. Long-term time series of the data is analyzed to assess the major spectral bands. In the monsoon regions there is a strong signal in the intraseasonal band. Composite analysis (e.g., Lawrence and Webster 2001) is then undertaken to assess the morphology of the intraseasonal variability relative to the intraseasonal peaks and valleys such as those observed in Figure 2. From the composite analysis a set of predictors can be determined. Both the predictor set and the predictand is band-passed to produce time series. The predictors used in the scheme are listed in Table 3. These sets are regressed using an evolving regression scheme (see Webster and Hoyos 2004) and recombined to form the prediction.

(ii) Discharge and precipitation predictions: The precipitation fields that are predicted are on the scale of Indian states (e.g., Orissa, Rajasthan) or regions (Ganges catchment, central India). Forecasts are made of 5-day (pentad) fields so that for a 20-day forecast, four lags are advanced. The forecasts are made for the Ganges and Brahmaputra river discharge and form Indian rainfall districts every 5 days throughout the summer commencing in May.

**(c) Short-term (1-10 days)**

(i) Model: Predictions of precipitation surface energy fluxes come from the operational ECMWF model. Each day, 51 ensemble members are used to determine future states over prescribed regions of South Asia. Statistical corrections similar to those discussed in (a) above are employed.

(ii) Hydrology Models: ECMWF model provides ensembles of precipitation forecasts which are used to force hydrological models. Two distinct hydrologic modeling approaches are used in a multi-model format: the "Data-Based Modeling" (Beven 2004) and "Distributed Modeling" (similar to the US National Weather Service). Both models are described in detail by Hopson (2005). The two model approach, employed for both the Ganges and Brahmaputra basins have certain attributes and drawbacks. Hopson (2005) shows that the results from the combination of models is better than either model used singularly. Observed discharge of the two rivers used to train models.

(ii) Prediction: Forecasts of regional

#### 4. Examples of the three-tiered forecasts:

An example of the seasonal outlook for the combined Brahmaputra and Ganges river discharge can be seen in Figure 5. The forecasts was initialized in April of 2004 . The upper panel shows the “plume” of forecasts from the 41 member ensemble while the lower panel show the probabilities (in the form of pie charts). The general expectation for seasonal forecasts for areas as small as Bangladesh ( $1.4 \times 10^5 \text{ km}^2$  or roughly the size of Wisconsin) would be that they would possess low skill simply because as the length of the forecast increases, uncertainty increase as the inverse of the area of the forecast. However, almost all of the river inflow into Bangladesh is accumulated in a catchment area that is 12 times the size of Bangladesh. As river discharge is essentially a weighted spatial and temporal integral of the rainfall over the catchment, a greater skill can be expected in seasonal outlooks of river discharge. In essence, the skill of forecasts of river discharge into Bangladesh is the integrated skill of the precipitation forecast over the much larger catchment areas of the Ganges and the Brahmaputra. Figure 5 shows that as early as April, 2005, the model predicted excessive discharge in July-August period. Although, 2004 was a relatively normal year compared to the great flood year of 1998 extensive flooding did occur throughout the country. Figure 6 plots the Brahmaputra river discharge throughout the monsoon season and shows that the danger level (dashed line) was exceeded during this period. Even though the current seasonal model is configured to give forecasts of the combined discharge of the Brahmaputra and the Ganges, it is clear that there is some skill in the forecast.

Figure 7 shows a summary of the 2004 forecast of central India region (defined in Figure 1) issues every five days for 20 days in advance. the lower panel shows the probability of anomalous precipitation for the dates indicated. Short-term forecasts (1-10 days) are shown in Figures 8a and b in two formats. Both refer to 10-day forecasts of river discharge. Figure 8a shows the results 10-day forecasts in ensemble mode. The observed Brahmaputra discharge (dashed line) falls within the spread of the ensemble members throughout the summer of 2004. The scheme also predicts with considerable accuracy exceedance of the danger level (horizontal dashed line) 10 days in advance. Using the spread of the ensemble members, it is an easy task to compute the probability of the exceedance of the danger level. This is shown in Figure 8b. We have found that threshold probability forecasting is the easiest form of presentation to understand.

## 5. Communication of forecasts:

Whereas the forecasting of an environmental event or the prediction of the probability of the exceedance of some limit (e.g., Figure 8b), unless the forecast is understood and used, there is no value in the forecast beyond academic achievement. Providing an understandable probability forecast is a challenge in both developed and developing societies. We have approached this problem by the development of a utility called the User Metric (Figure 9). The principal aim of a User Metric is to allow the transformation of probabilistic forecasts (difficult to understand and apply) to a usable assessment of aggregate risk (easy to understand) so that a deterministic decision of future action can be made (easy to apply). A User Metric should have the following properties:

- (i) *Incorporation of a probabilistic forecast of some pertinent parameter* (e.g., river discharge, rainfall variability (upper left panel Figure 9). These are supplied by the physical scientists/forecasts offices using the forecast modules described above. We note that the probability density function will change with each forecast.
- (ii) *Incorporation of local knowledge of the impact of an environmental of a given severity.* This can be in the form of a costing function provided by the user community (top right panel Figure 9). The costing function provides a quantification of the impact of a range of meteorological events (impact of no rain, moderate rain,

heavy rain and etc., on yield of a particular crop) of different severity on a particular application. The cost function is independent of a particular forecast and merely states the user's view of the impact of an environmental state. For example, at the time of planting of a crop, no rainfall would be disastrous, moderate rainfall is beneficial, too much rainfall may cause floods. However, later in the season, say at harvest time, there would be a completely different costing function on the same parameters

- (iii) *An easily comprehensible and visually decipherable representation of risk.* It is necessary to combine the probabilistic predictions with the costing functions to provide an aggregate risk analysis (bottom panel Figure 8). Such a measure provides a user community with an optimal at a particular time for a given circumstance. This visual analysis will aid the user community in making reasoned decisions by the generation of an aggregate risk analysis.

The example illustrated in Figure 9 is relatively straightforward. The question is whether or not a farmer should harvest all of his crop ahead of maturation (thus having zero risk of environmental damage but accepting a lower yield), wait until maturation (taking a chance of reduced yield due to environmental factors but noting that there is a chance that full yield will be achieved) or harvesting partially in order to spread risk and benefits. The problem then is choose the best strategy to hedge against uncertainty. First, the farmer knows that if heavy rains occur there will be a certain reduction of yield. This is the costing function. Also, if the forecast calls for a very high probability of dry weather then the harvesting strategy will be clear. But for a wider range of possible future states, the strategy is less clear and it is necessary to combine the probabilistic forecast with the costing strategy to come up with an optimal hedging strategy.

A basic tenet of our work is that we believe that there is important and valuable information in estimating risk of the occurrence of some event to which the user community is sensitive (e.g., floods), even when this risk is small but non-zero. Probabilistic forecasts offer the only way in which reasoned decisions can be made by the user community or relief organization. There appears to us no need to make decisions without computing probabilities of occurrence and ascertaining the cost/benefit relationship of a particular event in agreement with Zhu et al. 2002. Finally, the User Metric offers a simple way to incorporate information from the user community, combine it with probabilistic forecasts from numerical or statistical models, and provide an easily interpretable graphic from which the reasoned decisions can be made.

## 5. Concluding Remarks:

Perhaps the most important conclusion from this study is that the creation of a useful forecast is not an easy task. Clearly, it is not possible for an operational entity such as ECMWF to be able to anticipate the needs or the cost functions of all user communities. A successful end-to-end system requires the injection of engineering decision tools such as those introduced into the Bangladesh system by the CFAB group. That is, intermediate groups are needed in between the forecaster and the user community. With the advent of ENSO forecasts in the late 1990's, the first attempts to produce end-to-end prediction systems but these rarely resulted in satisfactory results. The intermediary groups in these schemes were principally social scientists lacking perhaps in the engineering approach necessary to produce quantitative interpretations of probabilistic forecasts. Whereas we can point to some success with the CFAB project it should be remembered that the bridge to other user groups will require different decision models and interpretations of probabilistic forecasts. CFAB, though, stands as a template upon which other systems can be patterned.

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## Figure captions:

- Figure 1: (a) The South Asian region showing the Brahmaputra and Ganges catchment areas and Bangladesh. Areas for which precipitation forecasts are routinely made (Central India, the Indian states of Orissa and Rajasthan, Bangladesh and the two major river catchment areas) are indicated on the map. (b) Entry points of the Ganges and the Brahmaputra into Bangladesh. River discharge is forecast on all three time scales at these points.
- Figure 2a: Pentad central India (W&H)
- Figure 2b: Daily rainfall within one active period (W&H)
- Figure 3a: Map of rainfall districts (W&H)
- Figure 3b: Temporal variability of rainfall (W&H)
- Figure 4: Schematic of overlapping three-tier forecast scheme
- Figure 5: Six-month forecast of the Ganges plus Brahmaputra river discharge into Bangladesh for June through November, 2003, commencing in May 2003. . Forecasts are made every month for a six-month period using the 41 members of the ECMWF coupled climate model. Red lines show the behavior of each ensemble member. The ensemble mean is shown as the solid line and the two dashed lines indicate plus and minus one standard deviation (sd) about the ensemble mean. The dotted line is the climatological river discharge. The lower panel shows the pdfs of river discharge relative to the color coding.
- Figure 6: Brahmaputra and Ganges discharge: 2004
- Figure 7: (a) 20-day forecast of Central Indian rainfall rate for the year 2003 using the Bayesian scheme developed by Webster and Hoyos (2004). The scheme predicts quite well the phase of the intraseasonal oscillations but underestimates the amplitudes of the peak periods. (b) Same but for Ganges discharge into Bangladesh. Forecast incomplete because of data problems. Time scale is in pentads.
- Figure 8: Example of short-term discharge forecasts into Bangladesh for Brahmaputra. The forecasts use the ECMWF ensemble precipitation forecasts in combination with a combination of statistical and distributed The red curve is the forecasts probability of the discharge being above danger levels which would indicate severe flooding. The black curve shows the percentage of the observed flow relative to the danger level.
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- The upper left panel shows the probability density function of some phenomenon (e.g., rain rate) produced by an environmental prediction group. Different user groups or the same user group at different times will have a cost/loss function associated with each of the probabilities. This family of user dependent outcomes can be seen in the upper right hand panel. Using some institutional context (e.g., individual, market based and etc.) a family of aggregate risk analyses can be made which reflect the

optimal decision for the particular user group. For the same forecast pdf, the aggregate risk analysis will be different. On the other hand, For one user group and a different forecast, there will be a different optimal strategy. The purpose of the bottom panel is to provide the user with one readily understandable diagram that takes into account the forecasts pdf and the particular user circumstances.



These are the figures of the manuscript. I thought that they would transport better in powerpoint mode than in attached ps. figures.

The book will be published in July, 2006. I will send you a final copy of the manuscript then if you are interested.

pjw

Figure 1 (a) South Asian region showing Brahmaputra and Ganges catchment & locations where 20-day precipitation forecasts are made. (b) Entry points of the Ganges and Brahmaputra into Bangladesh. Seasonal (1-6 months), intraseasonal (20-30 days) and short-term forecasts (1-10 days) are made for discharge at these points.

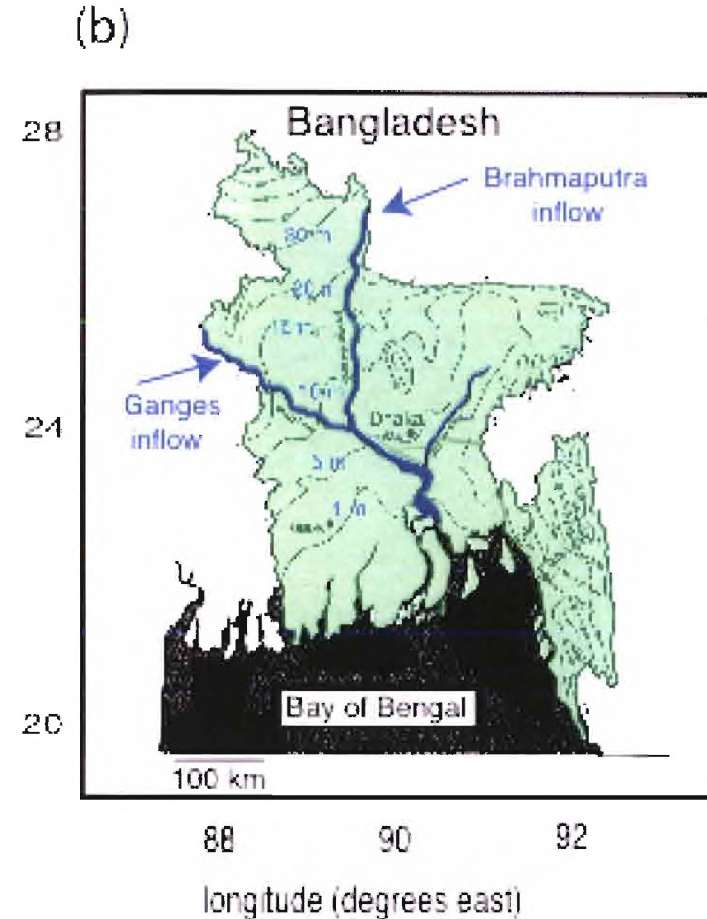
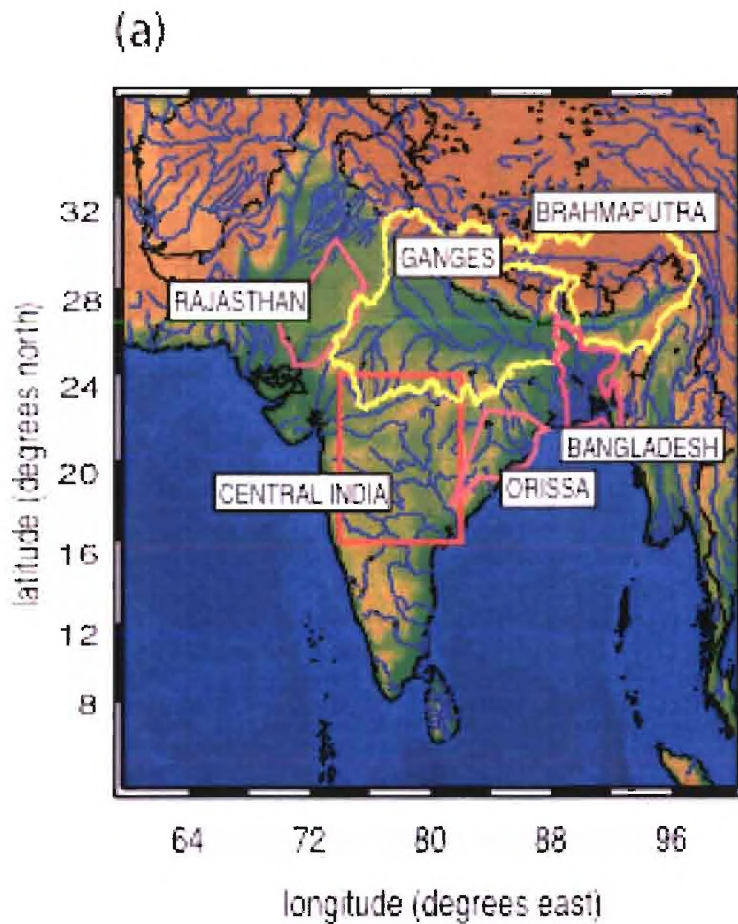


Figure 2a: Time series of central Indian rainfall (see Figure 1) from 1968-2002

(a) Central India pentad GPI rainfall for 1986-2002

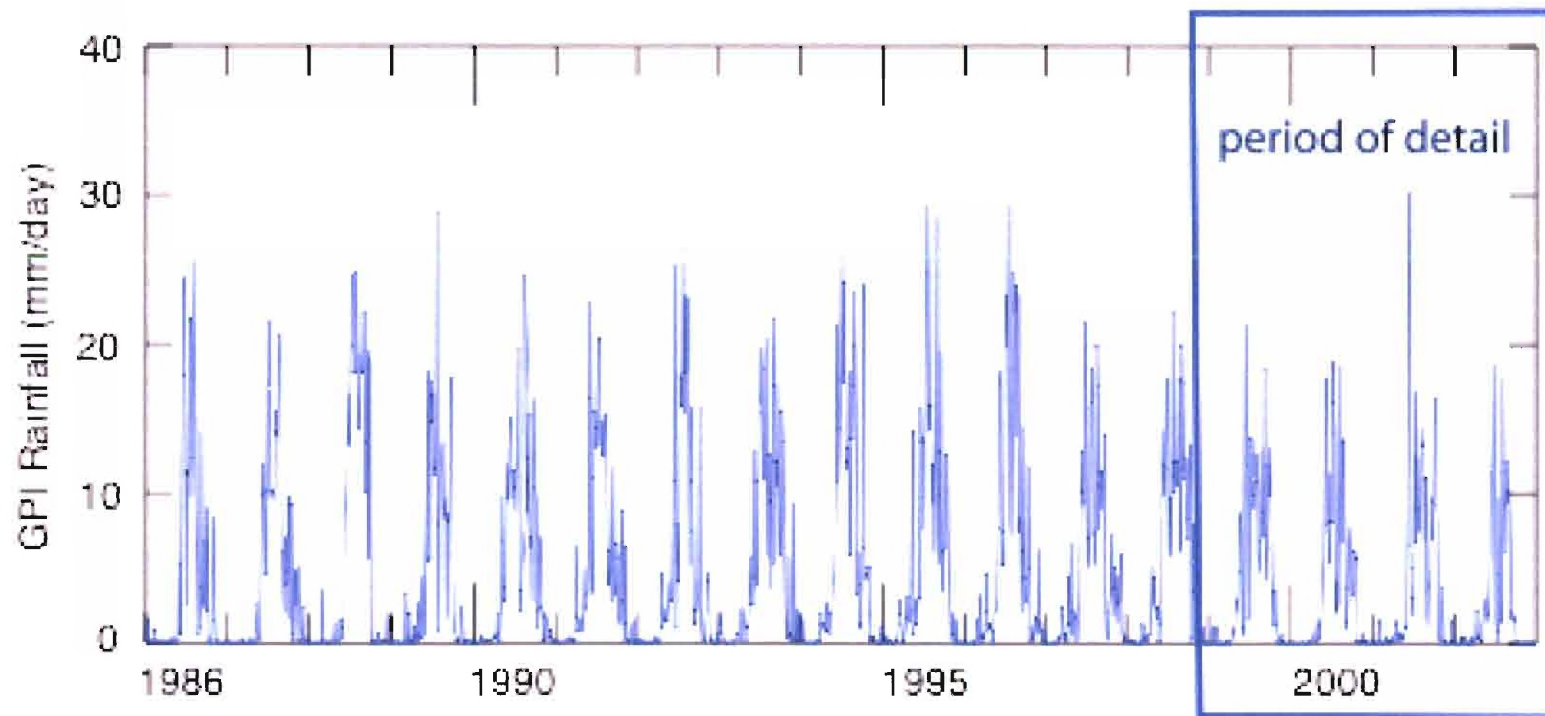
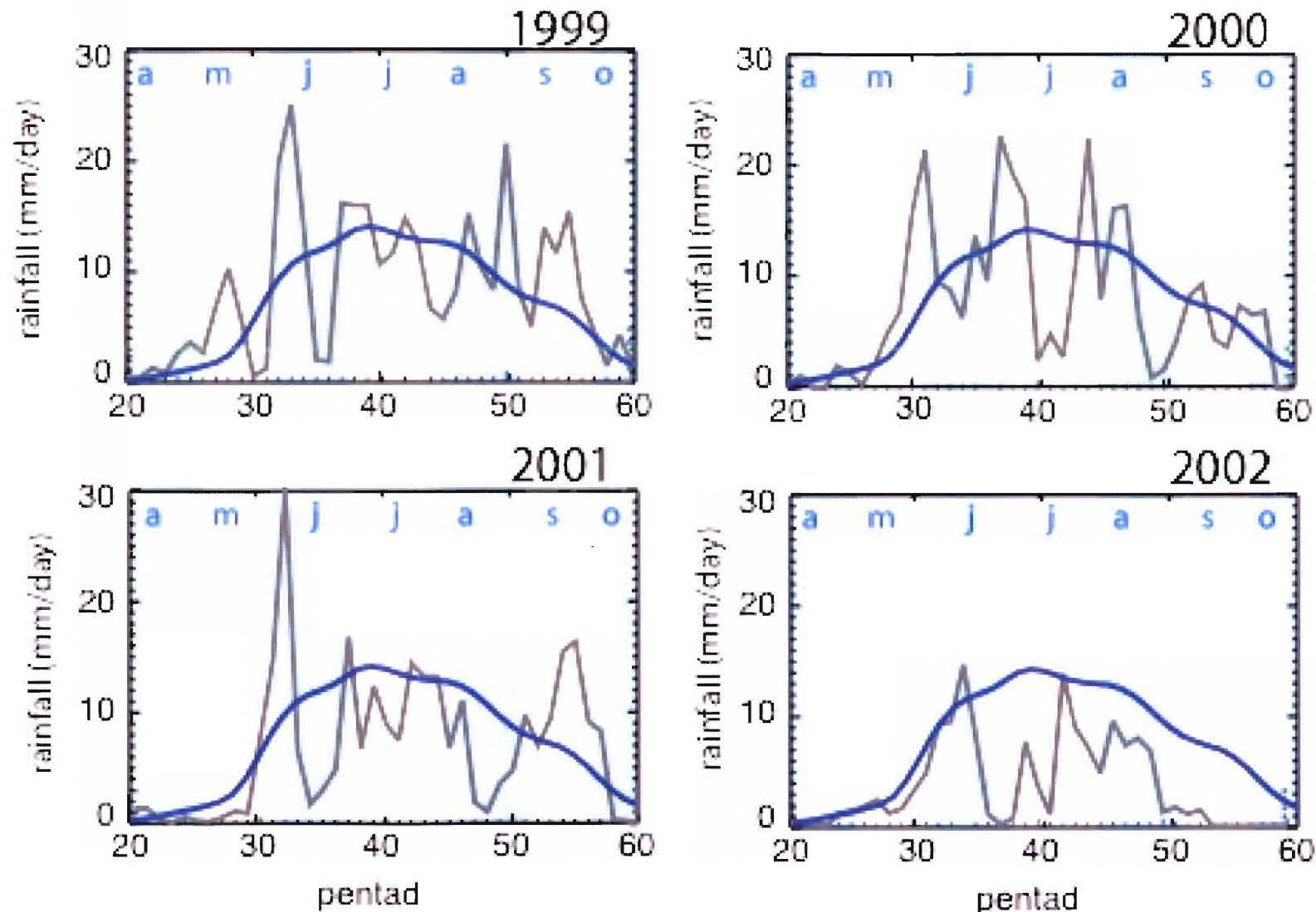


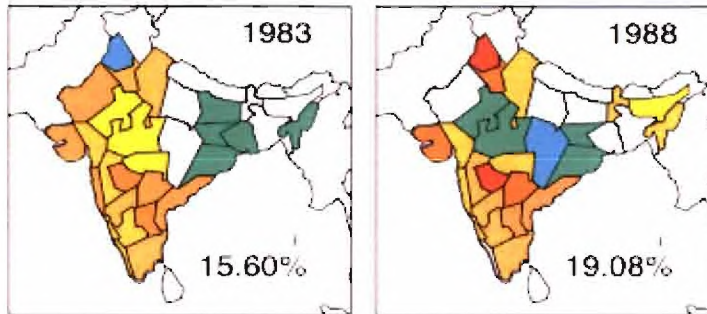


Figure 2b: Variability of rainfall in Central India during four years. The years 1999-2001 are indistinguishable in their mean total rainfall but their intraseasonal variability is markedly different and of extremely high amplitude. Blue curve is long-term average.

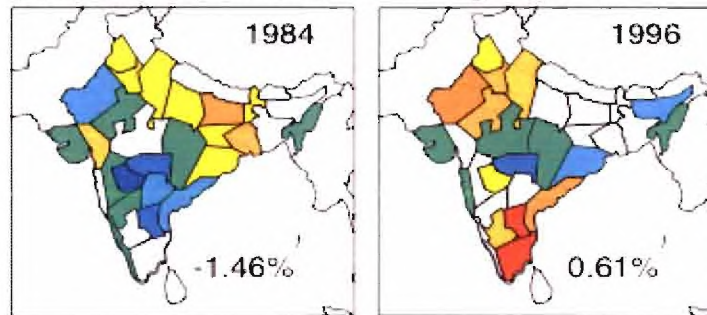
## (b) Central India pentad GPI rainfall for 1999-2002



(i) >115% summer average



(ii) 98% to 101% summer average



(iii) < 90% summer average

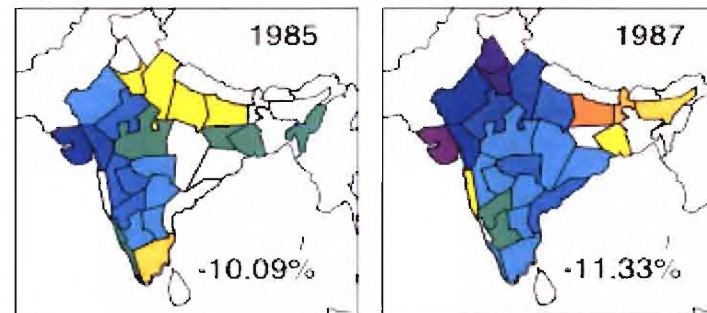
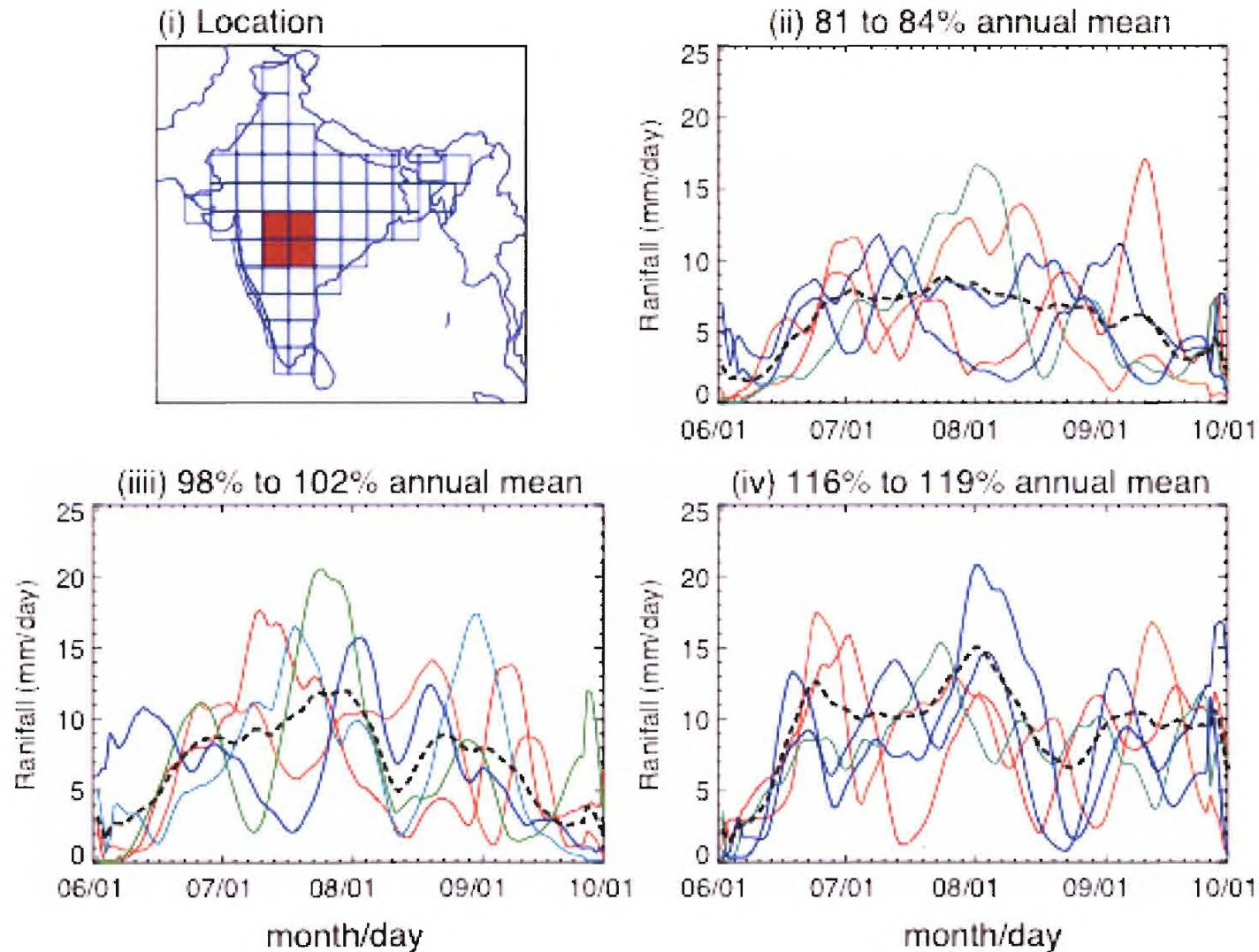


Figure 3a: Regional rainfall patterns for years very much above average (upper row), average (middle) and below average (bottom). Even in extreme years there are regions that are of the opposite sign to the seasonal anomaly. In addition, most years occur within  $\pm 5\%$  of average and there is no skill in regional seasonal forecasting for this more regular form of anomaly.



Figure 3b: Temporal variability of rainfall in Central India (red boxes) relative to long-term averages (dashed lines) for (i) well below mean, (ii) about average and (iii) well above average. There is no statistically significant difference between the timing of the timing of the intraseasonal variability irrespective of the mean rainfall.



3

Six-month forecast of the Ganges plus Brahmaputra river discharge into Bangladesh for June through November, 2003, commencing in May 2003. . Forecasts are made every month for a six-month period using the 41 members of the ECMWF coupled climate model. Red lines show the behavior of each ensemble member. The ensemble mean is shown as the solid line and the two dashed lines indicate plus and minus one standard deviation (sd) about the ensemble mean. The dotted line is the climatological river discharge. The lower panel shows the pdfs of river discharge relative to the color coding.

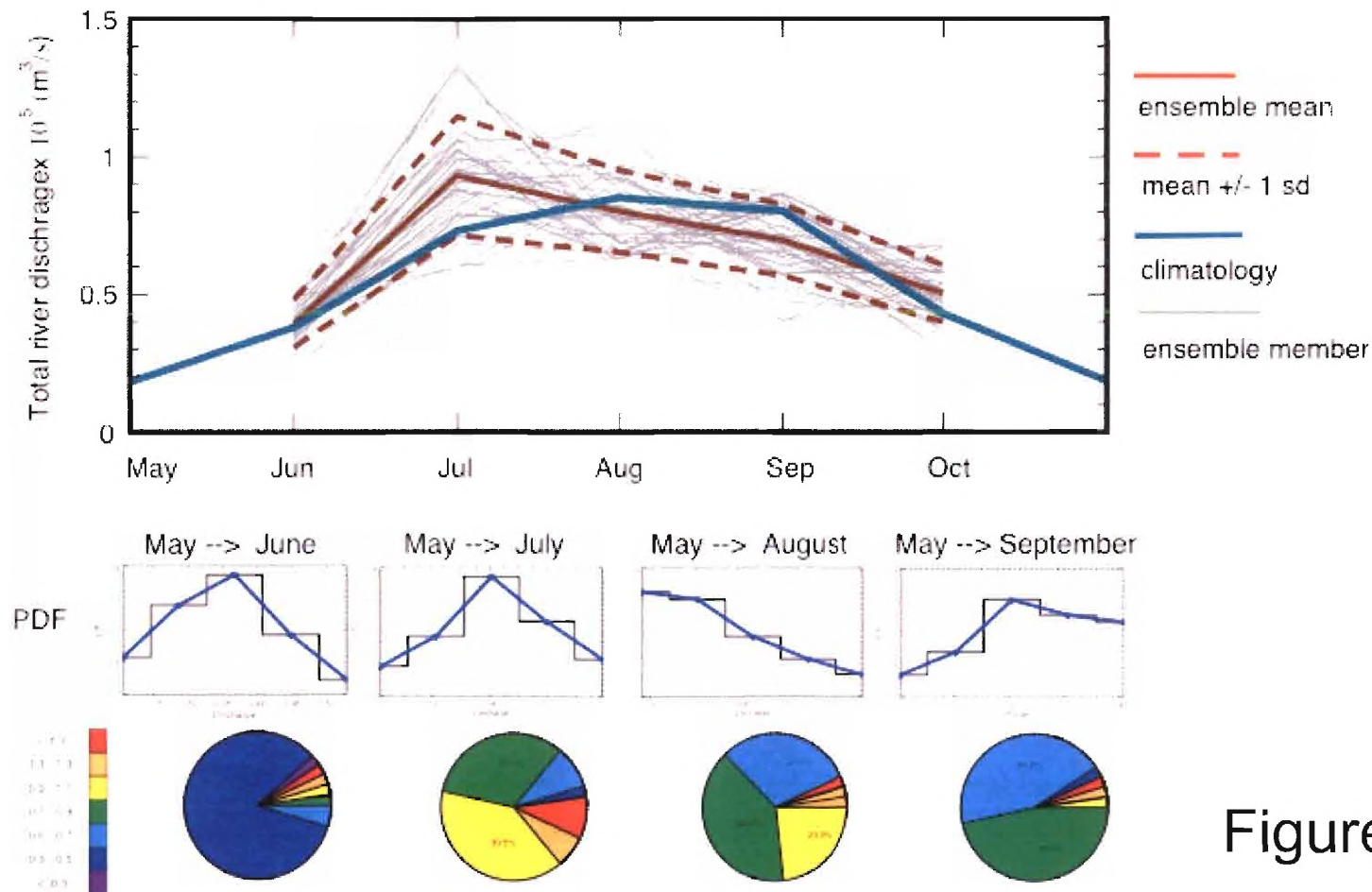


Figure 5:

Figure 6: Brahmaputra (blue) and Ganges (red) river discharge into Bangladesh during 2004. Horizontal lines indicate flood or danger levels. Comparing the time of exceedance of the Brahmaputra flood levels and the forecast (Figure 5) made May 1, 2004, it is clear that floods were accurately forecast 2-3 months in advance.

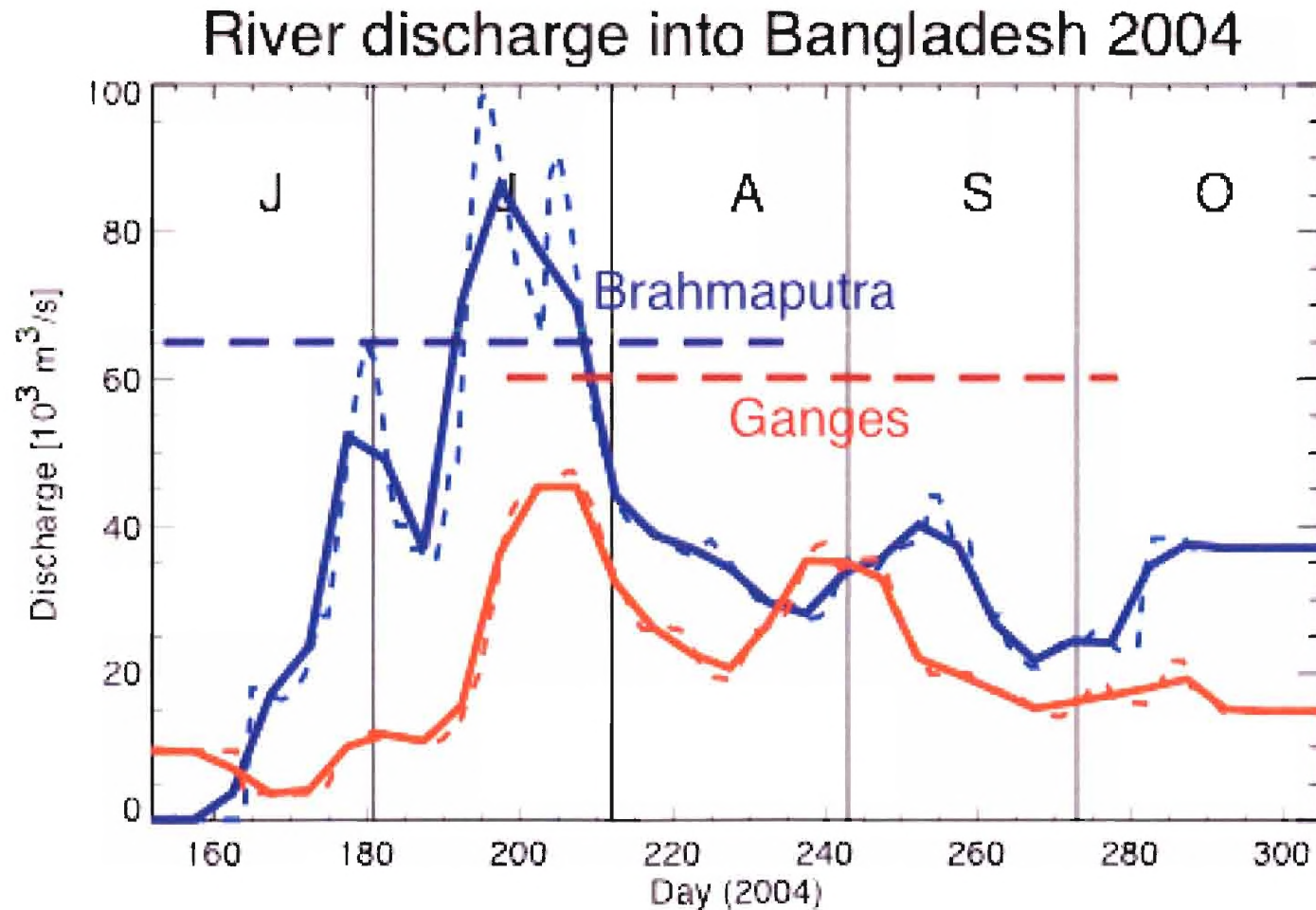
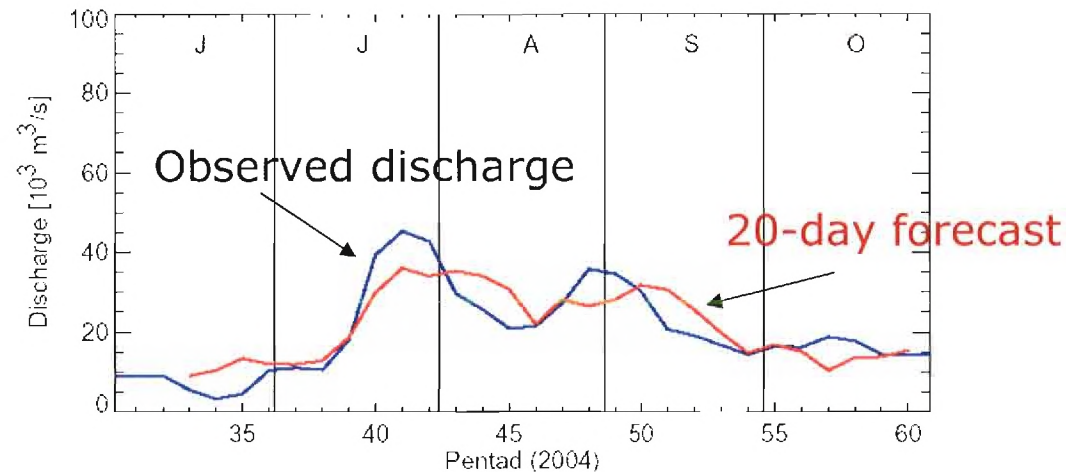


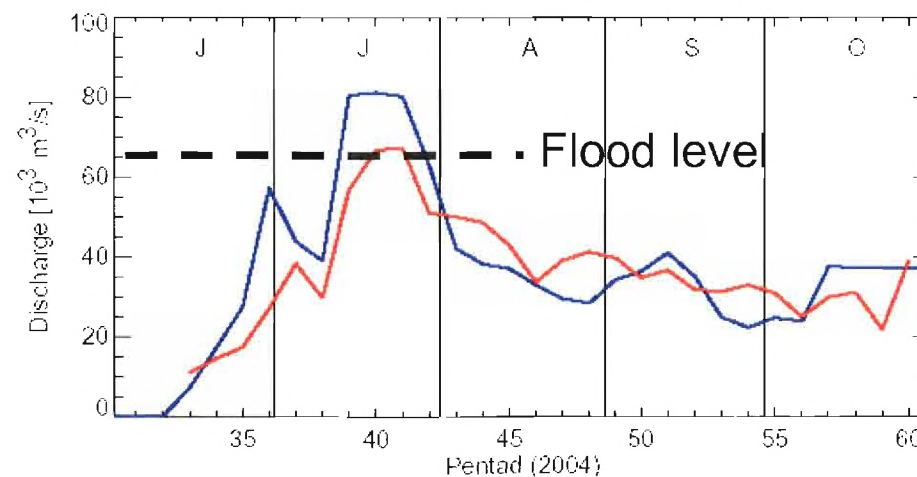


Figure 7: 20-day forecast of the Brahmaputra and Ganges discharge for 2005. Observed (verification) in blue, 20-day forecast in red. Note that the Brahmaputra flood level exceedance was forecast 20-days in advance. Although slightly late, the forecast probability was high 10 and 5 days prior to exceedance

## Ganges 20-day



## Brahma 20-day



Example of short-term discharge forecasts into Bangladesh for Brahmaputra. The forecasts use the ECMWF ensemble precipitation forecasts in combination with a combination of statistical and distributed The red curve is the forecasts probability of the discharge being above danger levels which would indicate severe flooding. The black curve shows the percentage of the observed flow relative to the danger level.

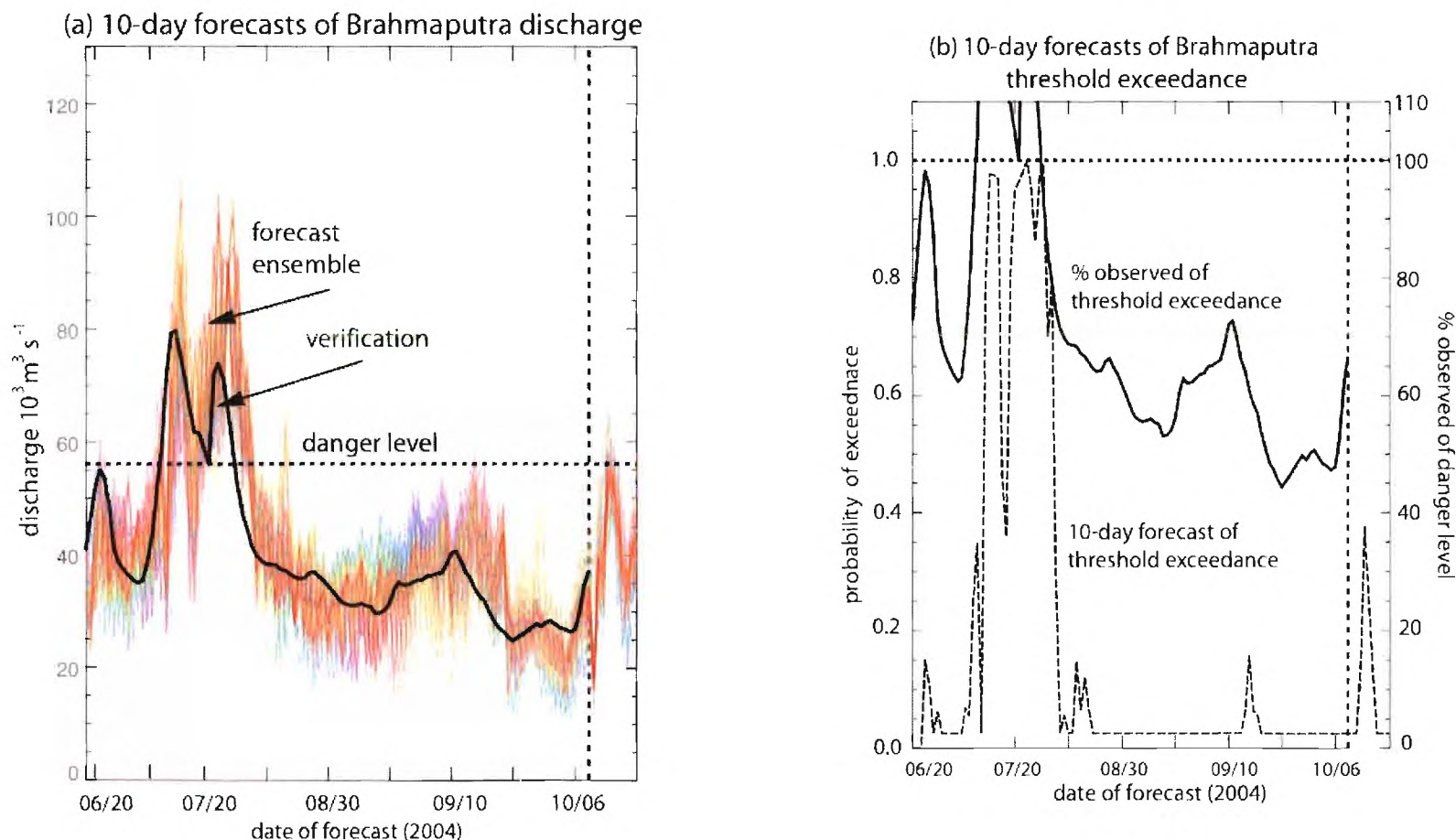
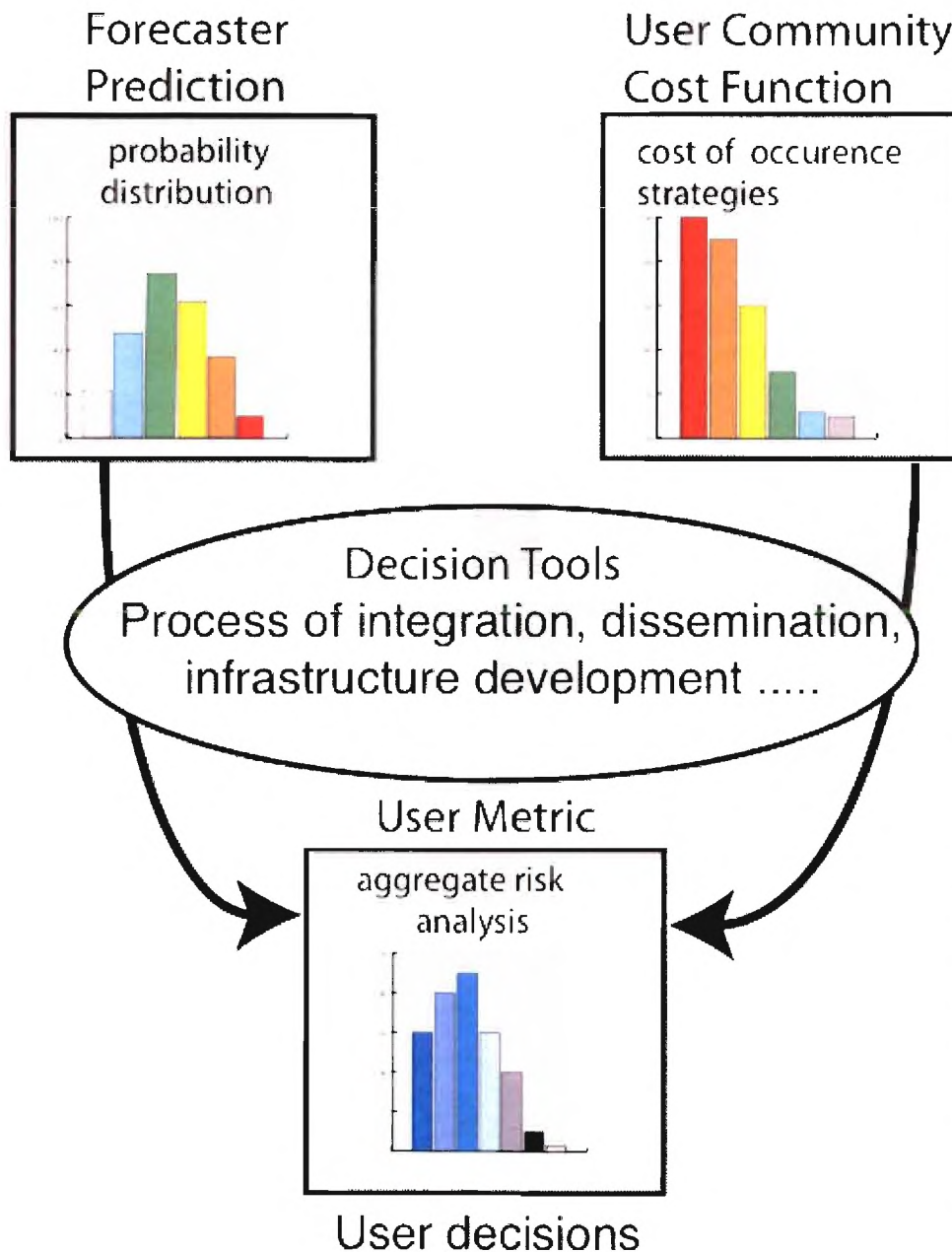


Figure 8: Note considerable skill in forecasting discharge and flood level exceedance probability potential at 10 days.



**Figure 8: The components of the User Metric.**

The upper left panel shows the probability density function of some phenomenon (e.g., rain rate) produced by an environmental prediction group. Different user groups or the same user group at different times will have a cost/loss function associated with each of the probabilities. This family of user dependent outcomes can be seen in the upper right hand panel. Using some institutional context (e.g., individual, market based and etc.) a family of aggregate risk analyses can be made which reflect the optimal decision for the particular user group. For the same forecast pdf, the aggregate risk analysis will be different. On the other hand, for one user group and a different forecast, there will be a different optimal strategy. The purpose of the bottom panel is to provide the user with one readily understandable diagram that takes into account the forecasts pdf and the particular user circumstances.